ABSTRACT

Dosimeters for ionizing radiation, based upon thermoluminescence in CaF_2:Mn, have been described by Schulman, et al., Rev. Sci. Instr. 31:1263 (1960). A miniature version, 1 mm diam and 13 mm long, has recently been developed at NRL. Groups of these dosimeters have been flown on six recoverable satellites, from which four payload capsules have been successfully retrieved and the dosimeters returned for readout. The polar orbits had apogees ranging from 306 to 578 km, and the satellites made 18 to 65 revolutions before recovery. The resulting absorbed doses for dosimeters shielded by 1.7 g/cm^2 of low-atomic-number material ranged from 1.8 to 4.5 millirad per orbit, based upon Co^{60} γ-ray calibrations. Dosimeters enclosed in an added 14 g/cm^2 Pb read about 43 percent less, in rough agreement with calculation based upon a trapped-proton spectrum. The observed readings are not inconsistent with the assumption that most of the proton flux was encountered in a region over the South Atlantic.

PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases is continuing.

AUTHORIZATION

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Project RR 008-03-46-5667
NASA Purchase Order S-16444G
AEC AT(49-7)-1864
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THERMOLUMINESCENT DOSIMETERS ON RECOVERABLE SATELLITES

INTRODUCTION

When a thermoluminescent material is exposed to ionizing radiation, the electrons released in the ionization process are trapped at lattice imperfections throughout the crystalline solid. These electrons remain trapped more or less permanently at room temperature, but are released by thermal agitation at some elevated temperature. When thus released, they recombine with positive charge carriers, and light is emitted in the process. The quantity of light emitted as the material is heated may be measured and related to the absorbed dose imparted to the material by the ionizing radiation. This heating process "erases" the phosphor, after which it is ready for another exposure.

This effect was first studied for dosimetry purposes by Daniels, et al. (1,2), using LiF and Al_2O_3, and by Kossel, et al. (3) with $Ca(SO_4)$:Mn.* Ginther and Kirk developed a special type of CaF_2:Mn having improved sensitivity and storage stability (5,6), and they investigated its application to dosimetry. Schulman, et al. (7,8) developed several forms of dosimeters based upon this phosphor, culminating in a device covering the range 10^{-3} to 3×10^5 rad of Co^{60} γ radiation.

A miniature version of the dosimeter, described in Ref. 9, has been developed at the U.S. Naval Research Laboratory. This dosimeter has a diameter of 1 mm and length of 13 mm and weighs about 16 mg. The linear γ-ray dose range is 10^{-2} to 3×10^5 rad (Fig. 1). Figure 2 is a photograph of several of the dosimeters and a Lucite holder mentioned later in this report. The CaF_2:Mn powder is contained in Pyrex glass tubing which is evacuated, outgassed, and sealed off to eliminate spurious effects resulting from the presence of atmospheric gases. The thermoluminescence is measured by means of an RCA 6199 photomultiplier positioned to collect light from one side of the dosimeter while a nichrome heater strip is pressed against the opposite side. The height of the observed glow peak, which is reached about 10 to 15 seconds after turning on the heater current, is used as the dose parameter. It is normally found to be reproducible with a standard deviation of roughly ±10 percent; the variability is caused mainly by variations in the effective heating rate.

SATELLITE APPLICATION

The wide linear dose range, relatively good storage characteristics, and small size of this dosimeter naturally suggested its possible usefulness in recoverable satellites and space probes.† A collaborative program was arranged between NRL and Lockheed Missiles and Space Company, to make it possible to try out the dosimeter in several satellites having recoverable capsules. For each flight the dosimeters were prepared at NRL, packaged at Lockheed, placed in orbit from Vandenberg AFB, recovered near Hawaii, sent to Lockheed for removal from the reentry capsule, and finally returned to NRL for readout of the thermoluminescence. Control dosimeters were sent along with the flight dosimeters to Vandenberg AFB, where they were retained until capsule-recovery time; they were then returned to Lockheed and thence back to NRL, along with the flight dosimeters. The flight characteristics

* For a review of more recent developments, see Ref. 4.

† It may also lend itself to use in nonrecoverable satellites or space probes, the data being telemetered to earth. This possibility is being explored at NRL.

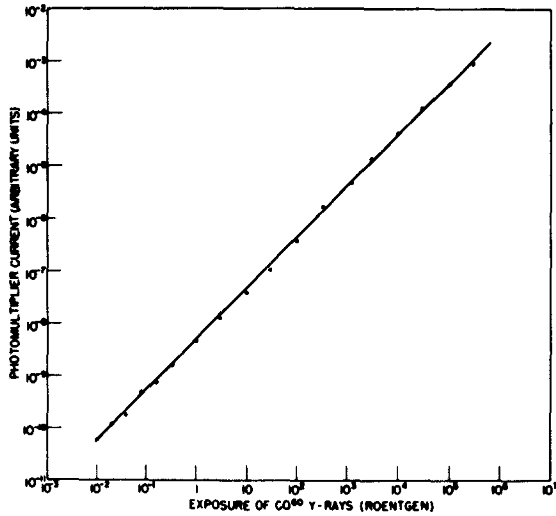

Fig. 1 - Response vs exposure of Co^{60} γ radiation for the miniature CaF_2:Mn thermoluminescence dosimeters

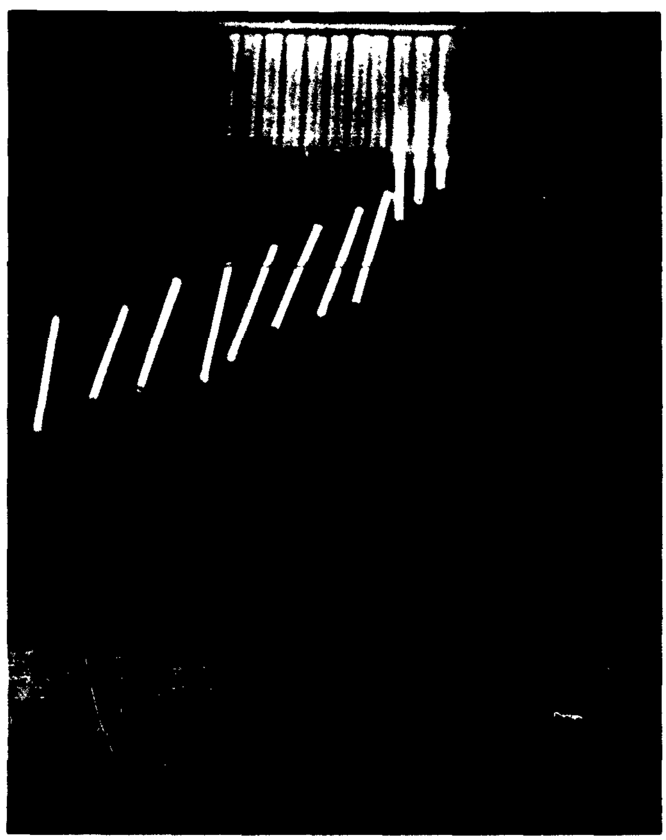

Fig. 2 - A group of miniature CaF_2:Mn thermoluminescence dosimeters and a Lucite holder for 11 such dosimeters. The Lucite holders on the satellite flights were similar, but only wide enough to hold 5 dosimeters.

of the four successful flights out of six attempted during the latter part of 1961 are given in Table 1. Corresponding data for a satellite flight described by Seward, et al. (10) are also included. This flight will be referred to later in the discussion as flight S-2.

PACKAGING

On each flight the dosimeters were enclosed in an aluminum canister filled with polystyrene foam for cushioning. This canister was located adjacent to the shell of the recovery capsule, so that the minimum amount of shielding material through which radiation passed to reach the dosimeters was 1.7 g/cm^2. The principal constituents of this mass were aluminum, 0.6 g/cm^2; phenolic glass, 0.5 g/cm^2; and nylon phenolic, 0.6 g/cm^2.

Two groups of dosimeters were flown on each flight. One of these groups, which will be designated as group A, was contained in holes bored in a Lucite block 1.3 mm thick × 8 mm × 16 mm, similar to but half as wide as the one shown in Fig. 2. This block was positioned in the polystyrene foam so that it was exposed to radiation which had passed through the minimum shielding (1.7 g/cm^2). The second group (B) was enclosed in additional shielding of lead. On flights 1 and 2 this amounted to 14.0 g/cm^2 Pb, the dosimeters being enclosed in a Teflon cushion 0.010 in. thick inside a lead cylinder. On flights 3 and 4 the group B dosimeters were held in a Lucite block, similar to that used for group A, which was taped inside a lead housing 3.6 g/cm^2 in thickness.

The aluminum canister also contained, on each flight, several Dupont type 555 dosimeter films capable of detecting Co^{60} exposure doses as low as 10 mrad, and a number of silver-activated phosphate glass rod dosimeters capable of detecting exposure doses of 10 rad or greater. None of the flights received radiation exposures of sufficient magnitude to be detectable by the glass-rod dosimetry system.

Table 1*
Satellite Flight Data

Satellite Parameters	Satellite Flights				
	1	2	3	4	S-2
Apogee (km)	563	578	306	502	421
Perigee (km)	150	232	246	243	243
Latitude at apogee	80.7°S	36.15°S	48.67°S	37.57°S	31.04
Latitude at perigee	80.4°N	38.69°N	60.5°N	40.33°N	35.24
Period (min)	91.55	92.41	89.84	91.85	90.95
Inclination (degrees from horizon)	82.02	82.70	81.56	81.23	82.70
Regression rate (degrees/pass)	23.00	23.20	22.6	23	22.9
No. of orbits	33	33	18	65	-

*The satellite identity, actual flight numbers, launch dates, and retrieval dates cannot be given here, since these data are now classified.

EXPERIMENTAL RESULTS

Table 2 contains a summary of the thermoluminescence data obtained from the four successful flights. The thermoluminescence readings, given in millirad (mrad),* represent the absorbed doses of Co^{60} γ radiation which were found in each case to give the same thermoluminescence response as that resulting from radiation exposure received during satellite flights. Fading corrections were made on the basis of recent data obtained with the miniature CaF_2:Mn dosimeters. These corrections are somewhat smaller than those given in Ref. 8. The percentage errors quoted with the data are the standard deviations† of individual dosimeters of a group from the group average. These figures are intended only to convey some idea of the degree of nonreproducibility of readings and do not refer to absolute accuracy. During the period in which these experiments were being carried out, intermittent difficulties were being encountered with the reproducibility of the heating cycle in the thermoluminescence reader. This was particularly noticeable in the flight 3 data, where the errors are so large that the observed magnitude reversal of groups A and B is meaningless.

DISCUSSION

The observed group A dosimeter readings differ significantly from flight to flight when taken on the basis of average reading accumulated per orbit (Table 2). This indicates that the amount of radiation encountered by the dosimeters varied either as a function of orbital geometry, or of time, or both.

Since the satellites were in polar orbits, where they would be exposed to protons coming from the sun in the event of a large solar flare, this possibility was examined. Only minor flares took place during the flights indicated in Table 1, and those that did occur were poorly correlated with the observed flight-to-flight variations in the thermoluminescence measurements. Only class 1 flares took place during flights 2 and 4, yet the data from those flights showed the largest average readings per orbit. One class 2 flare occurred during each of flights 1 and 3, yet the dosimeters on these flights showed the lowest readings per orbit. Evidently solar activity does not directly control the observed variations.

A more satisfactory explanation relates to the altitudes and orientations of the orbits followed by the four satellites. Those whose apogee was highest, and located at southern latitudes in the region of the South American anomaly (where the earth's magnetic field is weakest, causing a lowering of the trapped radiation belt), showed the greatest readings per orbit. Flight 2 had the highest apogee (578 km), occurring at 36.15°S latitude. Seward, et al. (10) have observed that the particle flux maximum on a similar flight (S-2, Table 1) occurred in the area between 30° and 40°S latitude and between 15° and 45°W longitude, over the South Atlantic. Seward's detector was a plastic scintillator biased against counting protons having energies less than 15 Mev and electrons less than 2 Mev. With this device the observed counting rates indicated the presence of a 4π flux of about 500 particles/cm^2-sec within the anomalous region.‡ Outside of this region the counting rate fell off gradually by more than 100-fold. Thus the favorable latitude and altitude of the apogee of flight 2 probably account for the relatively high dosimeter response on that flight. Flight 1 had an apogee nearly as high as that of flight 2, but it occurred at 80.7°S latitude, well away from the anomalous zone. Flight 4 had its apogee at nearly the same favorable latitude as did flight 2, but its

*An absorbed dose of 0.843 mrad will be deposited in CaF_2:Mn when it receives an exposure dose of 1 milliroentgen of Co^{60} γ rays under conditions of charged particle equilibrium, assuming W_{air} = 33.7 ev.

†As defined, for example, by Beers (11).

‡This figure was supplied by Dr. Seward after a preliminary evaluation of his data. It is stated to be probably accurate only within a factor of 2 or 3.

Table 2
Summary of Thermoluminescence Dosimeter Data*

Dosimetry Parameters	Satellite Flights			
	1	2	3	4
No. of dosimeters per group	3	3	5	5
Added shielding on group B (g/cm² Pb)	14	14	3.6	3.6
Avg. thermoluminescence readings (mrad)				
Group A	110	172†	42	204
Group B	77	113	46	174
Controls	31	37‡	12	9
Correction for fading of stored signal during time between flight and readout	11% (11 days)	10% (6 days)	10% (7 days)	10% (6 days)
Corrected net thermoluminescence readings				
Group A	89 mrad ± 8%	150 mrad ± 4%	33 mrad ± 47%	217 mrad ± 11%
Group B	52 mrad ± 10%	84 mrad ± 17%	38 mrad ± 24%	183 mrad ± 10%
Average reading of Group A dosimeters per orbit (mrad/orbit)	2.7	4.5	1.8	3.3
$\frac{\text{Group B}}{\text{Group A}}$	0.58	0.56	1.15	0.84

* See text for explanations of figures and standard deviations.
† Average of two dosimeters. The third was broken in transit.
‡ Estimated from flight 1 control data. No separate control package was available for the return trip of the flight 2 dosimeters from Lockheed to NRL.

altitude was considerably less (502 km as compared with 578 km). Consequently the dosimeter response per orbit was less on flight 4 than on 2. Flight 3 was very low (apogee of 306 km), and its latitude was also unfavorable. Thus it showed the lowest response per orbit of all the flights.

A similarity in the latitude of the apogees of flight 2 and of Seward's second satellite flight (S-2, Table 1) makes possible the following rough calculation, which shows that a major contribution to the observed group A dosimeter readings on flight 2 probably comes from a high proton flux encountered while passing through the anomalous region. The proton flux in the anomalous region will be assumed to have the spectral-energy distribution found at the lower fringe of the trapped-particle belt by Heckman and Armstrong (12), and shown by curve a in Fig. 3. Seward's scintillating detector was shielded by 0.21 g/cm² Al, which modified the spectrum of protons arriving at his scintillator to that shown by curve b.*

* This and the other spectral modifications shown in Fig. 3 are based upon the proton range vs energy data given by Rich and Madey (13), and upon the calculation method described by Noyes and Brown (14).

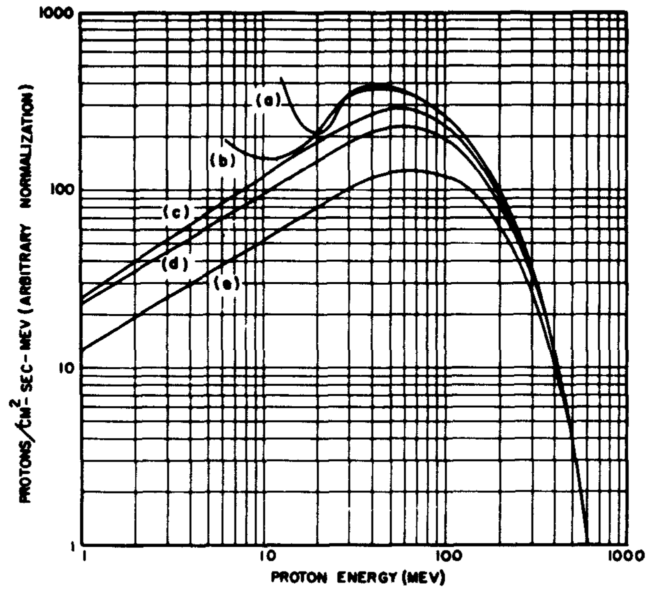

Fig. 3 - Energy spectrum of protons in the lower Van Allen belt as determined by Heckman and Armstrong (12). Curve (a), unfiltered; (b), filtered by 0.21 g/cm^2 Al; (c), filtered by 1.7 g/cm^2 Al; (d), filtered by 1.7 g/cm^2 Al and by 3.6 g/cm^2 Pb; (e), filtered by 1.7 g/cm^2 Al and by 14.0 g/cm^2 Pb.

Taking the flux to be zero at 600 Mev, curve b is integrated over the energy range down to Seward's cutoff-bias energy of 15 Mev. This area is then normalized to the particle flux observed by Seward (assuming it to be entirely protons), first taking into account the difference in altitude of the apogees of Seward's flight and flight 2, 421 and 578 km, respectively. From Fig. 6 in Ref. 15, one can estimate that the proton flux encountered in the anomalous zone by flight 2 was some ten times that on Seward's flight, or about 5000 protons/cm^2-sec, which is the figure to be used in the above normalization. The result is that the curves of Fig. 3 can be made absolute for flight 2 by decreasing their ordinates by the factor 0.0941.

The group A dosimeters were shielded by 1.7 g/cm^2 Al and nose-cone material. The spectrum of protons reaching them through this material (assumed to be entirely aluminum for calculation purposes) was that shown by curve c in Fig. 3. To find the absorbed dose which would be deposited in the thermoluminescent dosimeters by this flux, one makes use of the curve in Fig. 4, which relates the absorbed dose rate in CaF_2:Mn (approximated by Al) to the proton flux, as a function of proton energy.

This curve was derived from the proton stopping power and range tables of Rich and Madey (13). It was assumed that protons arriving at the phosphor in the dosimeter with less than 8 Mev would be completely stopped within it. This was based upon the fact that a proton crossing the diameter of a dosimeter perpendicularly to the axis encounters about 116 mg/cm^2 of phosphor, which will just stop an 8-Mev proton. For energies from 8 to 30 Mev the proton energy loss in the phosphor was computed from the difference in range of an entering and exiting proton. Above 30 Mev the energy loss was based upon the stopping power of the entering proton.

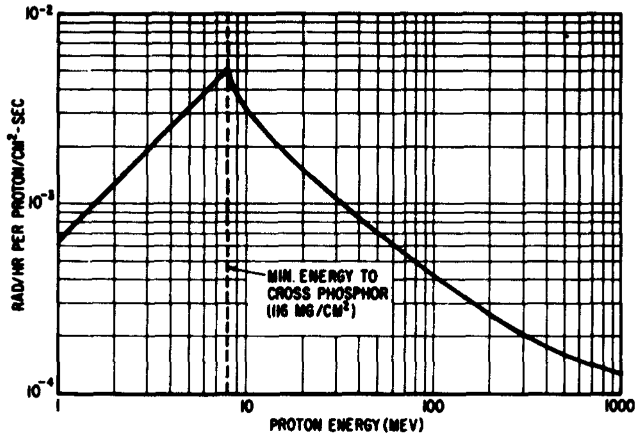

Fig. 4 - Absorbed dose rate per unit proton flux, averaged over the volume of CaF_2:Mn in a dosimeter. The dosimeters have an inner diameter of about 0.74 mm and are filled with phosphor powder to a density of 1.57 g/cm³, giving 0.116 g/cm² mass thickness across the diameter (see the text for additional details about the calculation).

The curve in Fig. 4 was multiplied by curve c in Fig. 3 to get a differential absorbed-dose-rate distribution, which was then integrated over the energy range from 0 to 600 Mev to get the absorbed dose rate in the group A dosimeters on flight 2 during transits through the anomalous zone. The result was 2.57 rad/hr.

The satellite spent only a small fraction of its orbiting time in the anomalous zone. The central part of the zone is only about 10 degrees wide in latitude, and its extent in longitude allows only two consecutive passes to traverse it. Thus only four orbital passes out of the total 33 could pierce the zone, and of these four passes only the fraction 10°/360° was spent in the zone. The fraction of time during flight 2 which was spent in the anomalous zone was thus $1/36 \times 4/33 = 0.0034$. Multiplying this figure by the dose rate in the zone, we get 0.0034×2.57 rad/hr = 8.7 mrad/hr for the time-average dose rate to be expected during the whole flight, assuming the proton flux to be zero outside of the central region of the anomalous zone. Table 2 shows that the measured average dose rate (assuming the response per rad to be the same for protons as for γ rays) was 3.0 mrad/hr. Considering the approximate nature of the calculation, the order-of-magnitude agreement with the above figure of 8.7 mrad/hr is adequate to show that anomalous-zone proton flux is probably a major contributor to the dosimeter readings.

Flight 4 had its apogee at nearly the same latitude as that of flight 2, hence a similar calculation to that above can be done for this flight also. The predicted time average dose rate for the group A dosimeters is about 3 mrad/hr, as compared with an observed 2.2 mrad/hr. The agreement here is fortuitously close.

The above calculations are based in part upon the assumption that the proton spectrum is that given by Heckman and Armstrong (12). The observed ratios of shielded to unshielded (group B/group A) dosimeter readings cast additional light upon this assumption. Curve d in Fig. 3 is the approximate proton spectrum resulting from passing the Heckman and Armstrong proton spectrum through 1.7 g/cm² Al and 3.6 g/cm² Pb; curve e is the corresponding spectrum resulting from 1.7 g/cm² Al and 14.0 g/cm² Pb. When the dose is calculated by the method previously outlined on the basis of curve d, and its ratio taken to that computed from curve c, the result is 0.83. It will be seen that this agrees very well with the corresponding value of 0.84 given in Table 2 for flight 4. Flight 3 had the same shielding, but the precision of the results is too poor to give a signficant ratio for group B/group A. The corresponding calculation from curve e gives a ratio of 0.50. This is 16 and 12 percent lower than the values of 0.58 and 0.56 obtained in flights 1 and 2 respectively. The cause of this discrepancy is not known, although it could be explained by the presence of a larger high-energy component in the proton spectrum than that indicated by the measurements of Heckman and Armstrong.

The absorbed doses indicated by the photographic dosimeter films which accompanied the group A thermoluminescent dosimeters were consistently lower in terms of equivalent Co^{60} absorbed dose than the doses indicated by the thermoluminescent dosimeters (Table 3). The explanation probably lies in a difference in the response per rad of the two detectors for high-energy protons, relative to their response per rad for Co^{60} γ radiation. A depressed response per rad for protons is to be expected with large-grain film such as Dupont 555, in which each grain of silver bromide becomes developable as a result of a single "hit" by either an electron or a proton. Thus a fraction of the proton energy is wasted in the film, resulting in a relatively low sensitivity for detecting protons as opposed to electrons. The corresponding proton efficiency of CaF_2:Mn is not known at present, but cyclotron experiments are being planned to obtain this information. Flight-to-flight variations in the ratios given in Table 3 are not readily explainable at this time.

Table 3
Comparison of Thermoluminescent and Film Dosimeters

Dosimeter	Satellite Flights			
	1	2	3	4
Dupont 555 Film (mrad)	64	98	18	116
CaF_2:Mn* (mrad)	89	150	33	217
Ratio $\frac{\text{Film}}{CaF_2:\text{Mn}}$	0.72	0.65	0.55	0.53

*Group A; see Table 2.

The possibility of vibration during takeoff and reentry contributing to the observed thermoluminescence was investigated by subjecting a group of dosimeters to severe vibration tests at Goddard Space Flight Center. These tests were designed to simulate 1.5 times the acceleration values encountered on launching a four-stage Argo D-8 vehicle. Such vibration levels are likely to be greater than those characteristic of the vehicle which was used in launching the present satellites. The resulting thermoluminescence response did not exceed that produced by 10 mrad of Co^{60} γ radiation. Thus the effect of vibration is probably negligible in the present results.

CONCLUSIONS

The observed readings of the thermoluminescent dosimeters can be generally accounted for on the assumption that they were exposed to a Heckman and Armstrong type proton flux during flight.

The flight-to-flight variations in the time-average dose rate can be qualitatively correlated to the altitude and latitude of the apogee in relation to the high-proton-flux region at the South American anomaly in the earth's magnetic field. Semiquantitative dose predictions can be made on the basis of the proton-flux measurements of Seward, et al. (10).

The miniature CaF_2:Mn thermoluminescent dosimeters are evidently applicable to the problem of space dosimetry in recoverable vehicles. Their precision is at present limited by the readout techniques, but improved methods are at present under development at NRL, promising reproducibilities within a few percent. These improvements involve the use of heater elements which are an integral part of the dosimeter, allowing a more reproducible heating cycle. This was the method used in the larger dosimeters described in Ref. 8, but until recently it was not found to be feasible to incorporate heaters in the miniature form of the dosimeters. The power required by these heaters is only of the order of one watt, which would not be excessive for use in satellites where the dosimeters are to be read out in place.

Additional experiments on recoverable vehicles should include flights which penetrate the trapped-radiation belt more deeply, especially with a variety of shields to measure the integrated dose vs shield material and thickness. The small size of the dosimeter, and its wide usable range of dose, would make it especially applicable for determining the dose as a function of depth in a human phantom on a recoverable satellite.

It is essential that the response per rad of CaF_2:Mn for protons be determined, so that the readings of the dosimeters can be related to absorbed dose in other materials (e.g., tissue). Such experiments are being planned with cyclotron proton beams.

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